DETERMINATION OF THE MOMENTUM SPREAD WHILE RUNNING IN THE ERL MODE AT THE S-DALINAC*

F. Schließmann†, M. Arnold, M. Dutine, N. Pietralla, Institut für Kernphysik, Darmstadt, Germany

Abstract

The recirculating superconducting electron accelerator S-DALINAC at TU Darmstadt is capable to run as a onefold or twofold Energy Recovery Linac (ERL) with a maximum energy of approximately 34 MeV or 68 MeV in ERL mode, respectively. After the final acceleration in ERL mode, the momentum spread at the intended interaction point (IP) has to be determined. In order to investigate that momentum spread, a nondestructive measurement method is necessary. For this reason, it is planned to expand the beam horizontally in a section close to the IP by providing a well-defined horizontal dispersion. Using a wire scanner in this section for measuring the horizontal profile of the electron distribution, one can determine the momentum spread. The method of determining the momentum spread using the horizontal dispersion and the design of the wire scanner are presented.

INTRODUCTION

The S-DALINAC at TU Darmstadt is a superconducting electron accelerator with three recirculating beamlines [1]. A floorplan is schown in Fig. 1. The maximum energy gain is 130 MeV using all three recirculating beamlines for acceleration. Due to its recirculating scheme and a special path length adjustment system [2], the S-DALINAC is capable to run also as a onefold or twofold Energy Recovery Linac (ERL) [3]. The onefold ERL mode was already demonstrated in 2017 [2], while the twofold ERL mode is not yet demonstrated. When running in ERL mode, the electrons are accelerated, interact at an intended interaction point (IP) and are then guided back to the accelerator and will pass it with an phase shift of roughly 180° in order to be decelerated. In this way, the electrons will lose their energy which will be stored in the cavities and can be used in order to accelerate subsequent electrons. Since only a onefold or twofold ERL mode is available at the S-DALINAC, the maximum energy gain in ERL mode is 34 MeV or 68 MeV, respectively, instead of 130 MeV. In order to set up a stable and effective ERL mode, certain requirements for synchrotron phase and longitudinal dispersion are necessary. These also influence the momentum spread (see definition in the next section). The aim is not only to achieve an effective ERL mode but also to achieve a small momentum spread at the IP.

Therefore, it is important to measure the momentum spread while running in ERL mode. For this, it is necessary to use nondestructive measuring methods. If a destructive method will be used, not only the beam will be blocked but also the ERL mode gets destroyed and so only the momentum spread generated by the conventional acceleration (CA) mode will be measured. At this time, it is still unknown whether the ERL mode leads to a different momentum spread than the CA mode, but since in the ERL mode the decelerated beam influences the electric field which accelerates the subsequent electrons, an impact on the energy gain and therefore on the momentum spread is expected. The influence of the ERL mode on the momentum spread can be determined by comparing the measured momentum spreads: once measured in ERL mode and once measured in the CA mode, i.e. with a beam blocked behind the IP. In the following, the definition of the momentum spread and the measurement method will be discussed in detail.

DEFINITION OF THE MOMENTUM SPREAD

Hereinafter, the subscript i indicates an individual electron. The relative momentum deviation δ_i is defined by $\delta_i := (p_i - p_0)/p_0$, where p_i is the electron's individual momentum and p_0 the design momentum. The quantity $\hat{\delta}$ denotes the centroid of the relative momentum deviation and is the arithmetic mean of all δ_i of the involved electrons. The standard deviation of all involved electrons' relative momentum deviation will be indicated by σ_δ and is the momentum spread, the quantity of interest. The hat as indicator for the centroid of a quantity and σ as indicator for the standard deviation of a quantity will be used in the following as well.

DETERMINATION OF THE MOMENTUM SPREAD

The aim is to measure the momentum spread σ_δ in a nondestructive way in order to keep the ERL mode alive. The best solution would be the usage of synchrotron radiation since it appears anyway while recirculating the beam. Mainly due to spatial constraints, it is unpractical to determine the momentum spread using the resulting synchrotron radiation in the intended section of the S-DALINAC. Furthermore, the horizontal dispersion in the dipole magnets is very small. Therefore, an alternative measurement method is necessary and that is the reason why a wire scanner will be used. A wire scanner is not perfectly nondestructive because it interacts with a part of the electron beam. Since it interacts only with a small fraction of the beam at a time (see details below), the vast majority of the beam remains unaffected and thus the ERL mode remains almost undisturbed. A wire scanner is therefore a good compromise and due to its specifications (see below) it can be considered as *quasi nondestructive*.

A wire scanner itself can be used to determine the transverse profile of the beam at position s. For a Gaussian beam profile in the horizontal plane, the standard deviation of it

---

[*] Work supported by BMBF through grant No. 05H18RDRB2 and DFG through GRK 2128.

[†] fschliessmann@ikp.tu-darmstadt.de

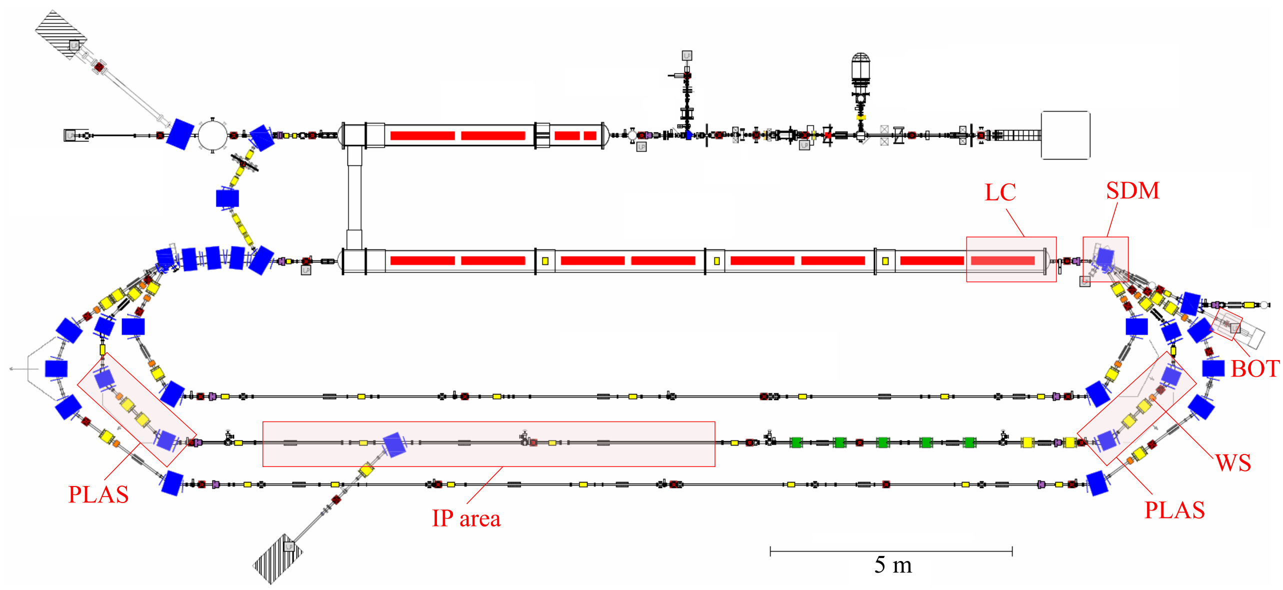

Figure 1: Floorplan of the S-DALINAC. Highlighted positions are the path length adjustment systems (PLAS) of the second recirculation beamline, the possible area for an intended interaction point (IP area), the last cavity (LC) of the Linac, the separation dipole magnet (SDM), the beryllium oxide target (BOT) for momentum calibration and the intended location of the wire scanner (WS) in order to determine the horizontal beam profile and hence the momentum spread.

can be described as

$$\sigma_x(s) = \sqrt{\varepsilon_x(s)\cdot\beta_x(s) + \left(R_{16}(s)\cdot\sigma_\delta(s)\right)^2}, \qquad (1)$$

where ε_x is the horizontal emittance, β_x is the horizontal betatron function and R_{16} is the horizontal dispersion [4]. The quantity of interest, the momentum spread σ_δ, can be deduced by rearranging Eq. (1):

$$\sigma_\delta(s) = \frac{\sqrt{\sigma_x^2(s) - \varepsilon_x(s)\cdot\beta_x(s)}}{|R_{16}(s)|}, \qquad (2)$$

if there exists a nonzero horizontal dispersion R_{16}. The beam profile is determined by the wire scanner (see details below). The emittance $\varepsilon_x(s)$ can be determined with a quadrupole scan [4,5], but there is no possibility to measure the betatron function $\beta_x(s)$ or the product $\varepsilon_x(s)\cdot\beta_x(s)$ at the intended section. Since $\varepsilon_x\cdot\beta_x \geq 0$, there exist an upper limit for the momentum spread

$$\sigma_\delta(s) = \frac{\sqrt{\sigma_x^2(s) - \varepsilon_x(s)\cdot\beta_x(s)}}{|R_{16}(s)|} \leq \frac{\sqrt{\sigma_x^2(s)}}{|R_{16}(s)|} = \frac{\sigma_x(s)}{|R_{16}(s)|} \qquad (3)$$

which can be determined, if the absolute value of the horizontal dispersion R_{16} is well-known. The upper limit of Eq. (3) has only a reasonable meaning if $\varepsilon_x\cdot\beta_x$ is significantly smaller than $\left(R_{16}\cdot\sigma_\delta\right)^2$ at position s. Since ε_x and σ_δ are intrinsic quantities of the beam and therefore fixed, the aim is to achieve a minimum for $\beta_x(s)$ and a maximum absolute value for $R_{16}(s)$ (under the condition that the beam does not expand more than the maximum possible measuring range as described in the next section). Since β_x can not be measured in the intended section, it can not be ensured whether the contribution of R_{16} to the beam size is dominant; a simulation of the intended location of the wire scanner at least suggests that this is the case and will be discussed in the next section.

As mentioned above, it is import to know the absolute value of the dispersion precisely. One can not rely on simulated values and therefore the dispersion has to be measured as well. From the equation

$$\hat{x}(s) = \hat{x}_0(s) + R_{16}(s)\cdot\hat{\delta}(s), \qquad (4)$$

which holds for the bunch's centroid [4], where $\hat{x}_0(s)$ is the design position of the bunch's centroid, $R_{16}(s)$ can be determined by measuring the change of the centroid position $\Delta\hat{x}(s)$ (with the same wire scanner) as a function of the change of the centroid of the relative momentum deviation $\Delta\hat{\delta}(s)$:

$$\Delta\hat{x}(s) = \Delta\left(\hat{x}_0(s) + R_{16}(s)\cdot\hat{\delta}(s)\right) = R_{16}(s)\cdot\Delta\hat{\delta}(s). \qquad (5)$$

The centroid of the relative momentum deviation can be varied by changing the amplitude of the last cavity of the Linac, if the single pass CA mode is used. A momentum vs. amplitude calibration can be done using the separation dipole magnet and a downstream located beryllium oxide target (see Fig. 1). It is not necessary (and not possible) to run in ERL mode to determine the horizontal dispersion, since the dispersion is a function of the lattice and the design momentum but not of the mode. After the momentum vs. amplitude calibration, the beam can be guided into the second recirculation beamline to the position of the wire scanner in order to determine the horizontal dispersion at the position of the wire scanner according to Eq. (5).

The measurement of the dispersion is easier for the onefold ERL mode than for the twofold ERL mode. For the onefold ERL mode, the beam will only be guided in the second recirculation beamline (because only this recirculation beamline houses a path length adjustment system capable to provide the ERL mode). In this case, the dipole magnets and quadrupole magnets are already tuned to the design momentum p_0 which will be existent in the onefold ERL mode. In the twofold ERL mode, the beam will first be guided into the first recirculation beamline and then into the second recirculation beamline. In this situation, the present dispersion at the wire scanner in the second recirculation beamline can not be measured, since neither a calibration is possible nor the beam will reach the wire scanner if the amplitude of the last cavity of the Linac will be changed sufficiently necessary. Hence, even in the case of the twofold ERL mode one has to measure the dispersion at the location of the wire scanner by guiding the beam directly in the second recirculation beamline, as in the case of the onefold ERL mode. In this case, the electrons are only accelerated once and the achieved momentum $\tilde{p}_0$ is not equal to the design momentum p_0 of this section in the twofold ERL mode. In order to reach the wire scanner, the dipole magnets and quadrupole magnets will be tuned to a design momentum of $\tilde{p}_0$. In order to keep the measured dispersion later on in the twofold ERL mode, the magnetic flux density of the dipole magnets and quadrupole magnets in the second recirculation beamline must be scaled by $p_0/\tilde{p}_0$ after the measurement of the horizontal dispersion.

REQUIRED DISPERSION

In order to get a high resolution, the horizontal beam size should be maximum at the location of the wire scanner. This can be achieved by a large absolute value for the horizontal dispersion (see Eq. (1)). While a large β_x leads to a large beam profile as well, it has to be ensured by a smart choice of the focusing strengths of the quadrupole magnets that the effect of R_{16} dominates in order to obtain a reasonable upper limit from Eq. (3).

The IP is located in a section where zero horizontal dispersion is desired, otherwise the beams horizontal position at the IP would be influenced by energy jitters. For this reason, the momentum spread must be measured at a location, where without doubt the same momentum spread exists as at the IP and where a sufficient horizontal dispersion can be generated. The bunch charge in ERL mode is at most 20 fC (at maximum current of 60 µA) at the S-DALINAC, while the energy is at least 20 MeV at the IP. Hence, the influence of space charge effects on the momentum spread are small over a distance of less than 20 meters [6], which is the maximum distance between the wire scanner and the possible location of the IP. Furthermore, the maximum energy in ERL mode is 68 MeV and the variation of the momentum spread due to synchrotron radiation while passing the last 45°-bending magnet of the arc before the IP can be neglected [6]. Therefore, the momentum spread existing at the IP can be considered as almost identical to that which will be measured 10 to 20 meters upstream in an arc which provides nonzero horizontal dispersion.

The wire scanner will be able to detect a beam profile over a maximum range of 35 mm which is the beampipe aperture in the intendend section. The expected momentum spread in ERL mode is about 10^{-2} to 10^{-3}. Therefore, a horizontal dispersion with an absolute value of 0.5 m to 5 m is aspired (compare Eq. (3)). In order to get a working point for the relevant arc, the tracking code *elegant* [7] was used. Figure 2 shows the results of the beam dynamics simulations using the emittances from [5] scaled to 68 MeV, which is the maximum energy in the twofold ERL mode. Without rearranging the already installed quadrupole magnets, a working point can be achieved so that the horizontal dispersion function R_{16} and its derivative R_{26} vanish at the end of the arc so that no dispersion will appear at the IP. The wire scanner can be placed at $s = 5.5$ m where the simulated value $R_{16} = 0.41$ m results (the actually present dispersion has to be determined as explained above). Due to spatial constraints, the wire scanner can not be placed in the first half of the arc, even if there exists a slightly larger dispersion. As visualized in

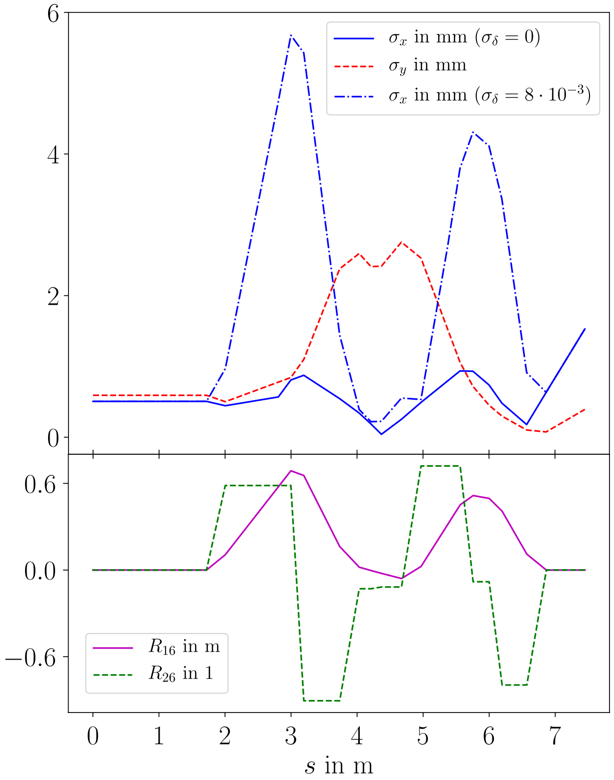

Figure 2: The plot shows the 1σ-envelopes of the horizontal and vertical beam size, the horizontal dispersion R_{16} and its derivative R_{26} in the arc where the wire scanner will be located in order to determine the momentum spread. For the horizontal plane, two cases are visualized: the envelope of the intrinsic beam size ($\sigma_\delta = 0$) and the envelope of a beam with $\sigma_\delta = 8 \cdot 10^{-3}$.

Fig. 2, the resulting intrinsic beam size $\varepsilon_x \cdot \beta_x$ has a value of 0.89 mm at the location of the wire scanner. Assuming that the beam has a Gaussian distribution and is within a $\pm 3\sigma_x$ environment, the momentum spread acceptance of the arc is roughly $\sigma_\delta = 8 \cdot 10^{-3}$, mainly limited by the large dispersion in the first half of the arc. If the momentum spread is $8 \cdot 10^{-3}$, a value of $\sigma_x = 3.45\,\mathrm{mm}$ will result at the location of the wire scanner. In this case, the upper limit $\sigma_\delta \leq 3.45\,\mathrm{mm}/|0.41\,\mathrm{m}| = 8.41 \cdot 10^{-3}$ follows from Eq. (3) which differs by only 5.1 % from the actual value. If the momentum spread is larger than $8 \cdot 10^{-3}$, the halo of the beam will be truncated and a different momentum spread results. If the momentum spread is smaller than $8 \cdot 10^{-3}$, a rearrangement of the quadrupole magnets is necessary, because in this way a smaller intrinsic beam size and a larger absolute value for the horizontal dispersion at the location of the wire scanner is possible.

DESIGN OF THE WIRE SCANNER

Since the beam will be extended horizontally as far as possible, the wire scanner must be designed so that it can detect the entire horizontal space inside the aperture. For this reason, only a vertically aligned wire is moved horizontally. Figure 3 shows a first draft constructed using the computer-aided design software *NX* [8]. It is not possible to use the established design of a double wire scanner to measure the horizontal and vertical beam size since otherwise the measurable region will be too restricted.

In order to justify the assumption that the measurement method is nondestructive, only a small fraction of the beam should be blocked by the wire so that the majority of the electrons can contribute undisturbed to the ERL mode. Therefore, in addition to a maximum beam size a minimum wire diameter is required. For this reason, a tungsten wire with a diameter of 100 µm100 µm is intended, which was suitable in a similar experiment [9]. With these properties, the deformation of the wire caused by the heating due to the interaction with the beam will be sufficiently small. Since the scanner is designed to only measure the horizontal beam profile, the wire can be shorter than in a double wire scanner. This also leads to a reduced wire deformation. The wire is tensioned in the fork over a distance of 26 mm. The span of the wire fixing fork has been selected to a maximum (limited by the vacuum chamber size) in order to not interact with the beam halo in vertical direction.

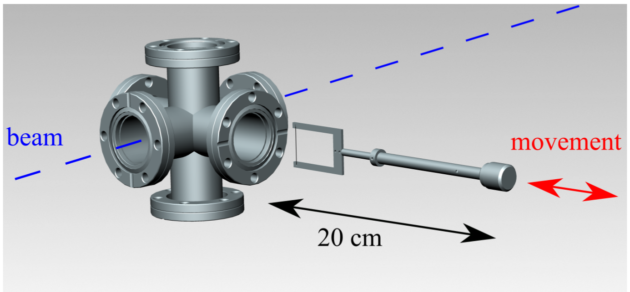

Figure 3: NX layout of the wire scanner. The beampipe, the bellow and the hydraulic cylinder are faded out. Additional diagnostic units such as an OTR target and a camera can be attached to the additional openings of the target cross.

While the beam interacts with the wire, secondary radiation will be emitted. The amount of this radiation is proportional to the electron rate and can be detected for example with a Cherenkov detector [9]. The horizontal beam profile can then be determined from the detected radiation in dependency of the wire's position.

CONCLUSION

In order to determine the momentum spread in the onefold or twofold ERL mode at the S-DALINAC, a nondestructive measurement method has to be used since otherwise the ERL mode will be broken. Therefore, a quasi nondestructive wire scanner in a dispersive section close to the intended interaction point will be used. Only a small fraction of the wire interacts with the beam and therefore the ERL mode keeps alive almost undisturbed. The interaction leads to secondary radiation which can be detected and leads to the horizontal beam profile, to the horizontal dispersion and hence to a reasonable upper limit for the momentum spread.

REFERENCES

[1] N. Pietralla, "The Institute of Nuclear Physics at the TU Darmstadt", *Nuclear Physics News*, vol. 28, pp. 4–11, 2018. `doi:10.1080/10619127.2018.1463013`

[2] M. Arnold *et al.*, "First ERL Operation of S-DALINAC and Commissioning of a Path Length Adjustment System", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 4859–4862. `doi:10.18429/JACoW-IPAC2018-THPML087`

[3] M. Arnold *et al.*, "ERL Mode of S-DALINAC: Design and Status", in *Proc. 59th Advanced ICFA Beam Dynamics Workshop on Energy Recovery Linacs (ERL'17)*, Geneva, Switzerland, Jun. 2017, pp. 40–44. `doi:10.18429/JACoW-ERL2017-MOIDCC006`

[4] H. Wiedemann, Particle Accelerator Physics, Fourth Edition, Springer-Verlag, Berlin Heidelberg, 2015.

[5] P. Dijkstal, M. Arnold, C. Burandt, F. Hug, and N. Pietralla, "Automated Transverse Beam Emittance Measurement using a Slow Wire Scanner at the S-DALINAC", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 817–819. `doi:10.18429/JACoW-IPAC2015-MOPHA020`

[6] F. Schließmann, dissertation in preparation, TU Darmstadt.

[7] M. Borland, "elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation," Advanced Photon Source LS-287, September 2000.

[8] Siemens Product Lifecycle Management Software Inc., NX 12.

[9] M. Dutine, Entwicklung und Test einer Messung der Strahlqualität am S-DALINAC, Master Thesis, TU Darmstadt, unpublished, 2018.